Laser-diode-pumped 1319-nm monolithic non-planar ring single-frequency laser

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Received April 11, 2003

Single-frequency 1319-nm laser was obtained by using a laser-diode-pumped monolithic Nd:YAG crystal with a non-planar ring oscillator (NPRO). When the NPRO laser was pumped by an 800-μm fiber coupled laser diode, the output power of the single-frequency 1319-nm laser was 220 mW, and the slope efficiency was 16%. With a 100-μm fiber coupled diode laser pumped, 99-mW single-frequency 1319-nm laser was obtained with a slope efficiency of 29%.

OCIS codes: 140.3570, 140.3560, 140.3480.

Single-frequency laser sources are required for many fields of fundamental research and scientific application, such as gravity-wave detection, coherent laser radar, coherent communication and fiber sensing. There are some reports on the single-frequency operation of diode laser pumped Nd:YAG lasers, but the transition wavelengh is concentrating on 1064 nm. Kane and Byer reported a monolithic non-planar Nd:YAG ring laser in 1985[1,2]. I. Freitag *et al.* have developed a series of diode-pumped single-frequency non-planar ring lasers required for the detection of gravitational waves[3-6]. In China single-frequency 1064-nm laser was also studied by different groups[7,8].

In the last few years single-frequency operation of a diode laser pumped Nd:YAG laser at 1319 nm is of interest since the 1319-nm laser locates at one of the major transmission windows of silica based fibers. But the oscillation of single-frequency 1319-nm laser is much more difficult compared to the 1064-nm single-frequency laser. Since the stimulated emission cross section of 1319 nm is 1/5 of that of 1064 nm in Nd:YAG, the threshold of 1319-nm oscillation will be much higher than that of 1064-nm oscillation, and the efficiency will be lower. For a stable oscillation of 1319 nm in Nd:YAG the 1064-nm oscillation must be suppressed and the neighboring transition at 1338 nm should also be eliminated.

Early reports on single-frequency 1319-nm operation of LD pumped Nd:YAG lasers include microcavity[9], discrete element versions of unidirectional ring lasers[10] and monolithic non-planar ring lasers[11]. Since the LD pumped monolithic non-planar ring laser has the properties of high intensity and frequency stability, a novel monolithic non-planar ring laser for 1319-nm oscillation was designed and developed in our group. As far as we know, it is the first time that single-frequency 1319-nm laser was generated from a laser diode pumped all-solid-state monolithic laser in China.

The principle of the NPRO is to eliminate the spatial hole burning by using the unidirectional ring resonator. There are different ways to design the unidirectional ring oscillator. The conventional configuration includes a polarizer, a Faraday rotator and a half-wave plate in the resonator. In the monolithic non-planar ring laser, all functions of the polarizer, Faraday rotator and half-wave plate, are incorporated into a single block of optically isotropic gain medium. The schematic diagram of the Nd:YAG NPRO is shown in Fig. 1. The ring path (*AB-BC-CD-DA*) is defined by four reflecting surfaces whose normals are not coplanar. The facets containing *B*, *C* and *D* are optically polished flat surfaces where total internal reflection occurs. The output coupler at *A* is a surface with a multilayer dielectric coating that is partially transmitting. Point *A* is not only pumping point but also the output coupling point. In Fig. 1, β is defined as non-planar angle and α is incidence angle of pump light. With a magnetic field *H* present in the direction shown in Fig. 1, the YAG crystal itself acts as the Faraday rotator. The three total internal reflections create an effect that is analogous to a rotation by a half-wave plate, and the output coupler acts as a partial polarizer. Thus the monolithic non-planar ring laser is a unidirectional ring laser with no discrete intracavity elements. To ensure an oscillation without loss, the manufacture tolerance of the angle and the angle between two normals of the facets containing *B* and *D* are of great importance. In our monolithic block the manufacture tolerance of the two angles is restricted to 1 minute.

The polarization states and their losses for the clockwise (CW) and counterclockwise (CCW) waves can be

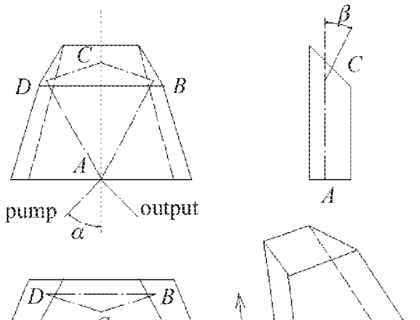

Fig. 1. Scheme of monolithic non-planar ring oscillators.

computed from the eigenvectors and eigenvalues of the Jones matrix describing one round trip in the ring. There are four eigenvalues for the resonator, two for each of the two directions of propagation around the ring. In general the eigenmode with the lowest loss reaches laser oscillation threshold first. Since the Nd:YAG laser transition is homogeneously broadened, the traveling-wave mode oscillating first consumes the gain uniformly and prevents the higher loss modes from reaching their threshold. In this way, unidirectional single-axial-mode operation of the ring laser is established and maintained.

By calculating eigenpolarizations of NPRO, the influences of each parameters inside cavity on the losses and loss differences of eigenpolarizations were carefully analyzed. These parameters include the magnetic field, the reflection coefficients (s and p polarizations) on the output coupler, the incidence angle and the non-planar angle. According to the calculated results, the non-planar angle β was chosen as 50° instead of usual 90°, which increases the loss difference between two eigenvalues by a factor of 20 and assures the single frequency oscillation. Finally a monolithic non-planar ring laser with a dimension of $14 \times 12 \times 4$ mm^3 was constructed. The crystal was placed in the field of a permanent magnet with an average field of 0.2 T.

For obtaining a stable oscillation of 1319 nm, the dielectric coating of the output coupler facet is of extreme importance. Three conditions have to be fulfilled simultaneously by the optical coating. It has to be highly transmitting at 808 nm for efficient pump light coupling, highly transmitting at 1064 nm to suppress the strongest 1064-nm transition, and optimal s and p reflectivities at 1319 nm laser wavelength are required. In our scheme s and p polarizations have different reflectivity of 98% and 85%, respectively. For eliminating the neighboring 1338-nm transitions the reflectivities of s and p polarization of 1338 nm is 1% lower than that of 1319 nm, in order to ensure the single-frequency operation of 1319 nm.

The above designed monolithic non-planar ring oscillator was experimentally studied by using two different pump sources. First a fiber coupled laser diode with a core diameter of 100 μm was used (pump wavelength 808 nm). The numerical aperture of the pumping fiber is 0.22. Figure 2 shows the 1319-nm single-frequency laser output power versus incident LD power. The pump threshold is 780 mW, and the slope efficiency is 29%. 99-mW single-frequency laser was obtained with a maximal pump power of 1.1 W. The emission wavelength was measured with an Anritsu MS96A optical spectrum analyzer. Figure 3 shows the measured emission spectrum of the monolithic non-planar ring laser. It is obvious that there is no emission at other wavelengths but 1319 nm in the region of $1.0 - 1.4$ μm.

For obtaining higher output power the NPRO was further pumped by an 800-μm fiber coupled diode laser (Coherent Inc.). In order to ensure the fundamental mode operation, the pump beam was imaged by two spherical lens with the focal length of 12 and 30 mm. The beam diameter of the pump laser was reduced from 800 μm to about 320 μm. The pump threshold is 910 mW, and the slope efficiency is 16%. Under the pump power of 2.2 W, 220-mW single-frequency laser output at 1319 nm was obtained. When the pump power was further increased, higher order transverse mode oscillated due to the big pump beam size and the laser was no longer in single frequency operation.

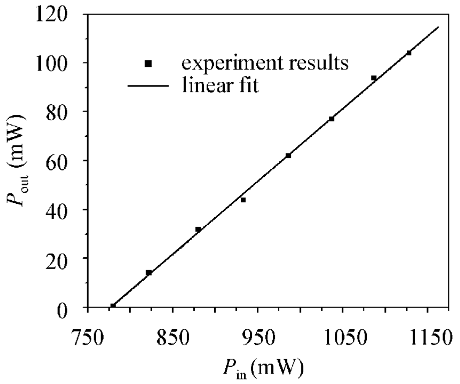

Fig. 2. The 1319-nm output power versus laser diode pump power.

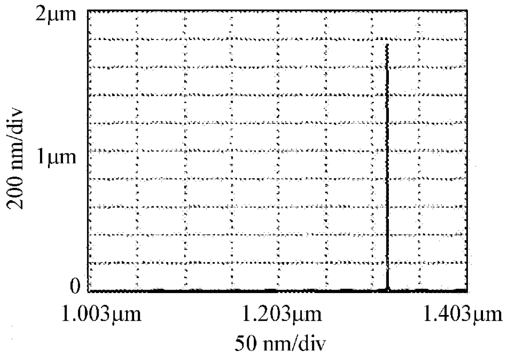

Fig. 3. Emission spectrum of the monolithic non-planar ring laser.

The spectrum of non-planar ring laser was measured by using a laser spectrum analyzer (the scanning Fabry-Perot (F-P) analyzer from Burleigh Inc.). Figures 4 and 5 show the measured laser spectra of the monolithic non-planar ring laser. First the space of the two high reflecting mirrors was set to 10 mm and the free spectrum range (FSR) of the scanning F-P analyzer is 15 GHz. For the two mirrors of F-P analyzer were originally designed for the high reflection at 1064 nm, the reflectivity at 1319 nm is relatively lower and the finesse in 1319 nm is only about 12. According to our design the longitudinal mode spacing of the non-planar ring laser is 5.4 GHz, which is much larger than the spectrum resolution of the scanning F-P analyzer. From Fig. 4 only one longitudinal mode can be found in one FSR and no other axial modes exist.

Furthermore the space of two mirrors of the F-P analyzer was increased to 50 mm, which means the free spectrum range is turned to 3 GHz. The spectrum of monolithic non-planar ring laser measured by the F-P with 3-GHz FSR was shown in Fig. 5. Since the finesse of scanning F-P analyzer is still 12, so the distinguished line width is now 300 MHz. From the cavity analysis the frequency difference between two neighboring transverse modes of the NPRO is in a range of 1 GHz when the pump induced thermal effect is considered. Figure 5 shows that

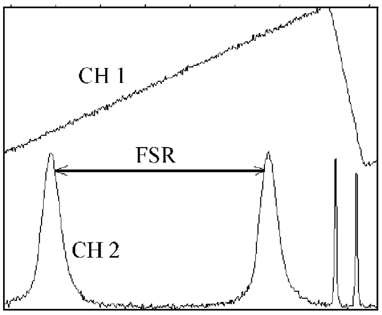

Fig. 4. The laser spectrum of monolithic non-planar ring laser (FSR = 15 GHz). CH1: the driving voltage of the F-P; CH2: the signal of the laser spectrum.

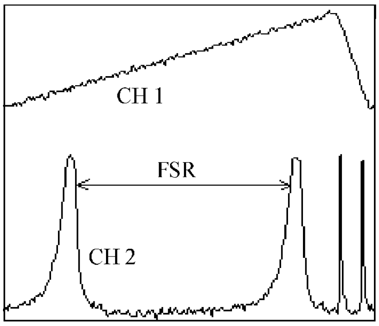

Fig. 5. The laser spectrum of monolithic non-planar ring laser (FSR = 3 GHz).

there are no other modes oscillating in a range of 1 GHz. So from Figs. 4 and 5, the measured 1319-nm laser oscillates in single-longitudinal and single-transverse mode (single frequency).

The transverse intensity distribution of laser beam was measured by using the moving slit method and a single element detector. A slit mounted on a translation stage is used to cut the beam in front of a fixed large area detector so that the detector measures the transmitted power as a function of the slit position. The intensity distribution of the 1319-nm beam is shown in Fig. 6. The transverse intensity distribution is perfectly fitted with the Gauss distribution.

In summary, 1319-nm single-frequency laser from the monolithic non-planar ring laser was reported. The laser oscillates in a single-longitudinal and single-transverse mode. 99-mW, 1319-nm single-frequency was obtained with a 100-μm fiber coupled laser diode and the slope efficiency is 29%. By using a high power pump source, 220-mW single-frequency 1319-nm laser was obtained.

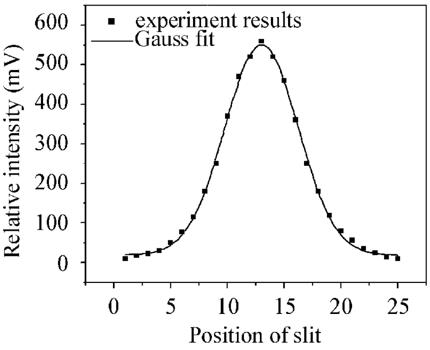

Fig. 6. The transverse energy distribution of laser beam.

This work was supported by the Tenth-Five Research Program and the Excellent Young Teachers Program of Ministry of Education, P. R. China. C. Gao is the author to whom the correspondence should be addressed, his e-mail address is gao@bit.edu.cn.

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